Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 56 (2016) 128 – 132

www.elsevier.com/locate/procedia

9th International Conference on Digital Enterprise Technology - DET 2016 – "Intelligent Manufacturing in the Knowledge Economy Era

Real-time Monitoring of Wind Turbine Blade Alignment using Laser Measurement

Oliver Mankowski, Qing Wang*

School of Engineering and Computing Sciences, Durham University, Durham, U. K.

* Corresponding author. Tel.: +00 44 191 334 2381; fax: +0044 191 334 2408. *E-mail address:* qing.wang@durham.ac.uk

Abstract

The aim of this paper is focused on using laser based metrology techniques to capture the positional changes of wind turbines in service and aligning drivelines in the turbines. In this way the mechanical operation, and therefore the aerodynamic design and loading predictions, of the turbine can be more accurately predicted and thus lead to greater optimization and improved efficiencies.

In order to perform real-time blade alignment, a laboratory test rig has been created that operates at the typical rotational rates of a wind turbine. This test will be conducted on both the radial misalignment and axial angular misalignment for a range of rotational speeds and torque loads. As such, a relationship for variation in alignment by rotational speed and torque will be determined, as well as presenting a method for real-time analysis of wind turbine blade alignment. Tests will also be conducted showing misalignment, and hence will show when the blade enters a state of requiring re-alignment.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Wind turbine blade alignment, laser metrology, data acquisition and analysis

1. Introduction

In recent years, with the changing climate and people becoming increasingly aware of environmental issues, there has been a huge increase in the use of low carbon techniques, particularly wind energy. In the UK, Government statistics (2013) [1] show that the contribution of electricity from renewable energy increased from 2.6% in 2000 to 11.5% in 2012 (a target of 15% has been set for 2020). Of this renewable energy, 47% is produced by wind power (29% is onshore and 18% is offshore). This is only expected to grow further.

In order for wind turbines to efficiently produce large amounts of energy, wind turbine blades must be extremely large. The nature of wind turbines demands expert design, manufacture, testing and maintenance of the equipment, particularly offshore where conditions are more severe. Minimizing measurement error provides manufacturers with confidence in the accuracy of the data, allowing the design of blade prototypes and more aerodynamically efficient blades along with other large-scale products.

The wind industry currently uses predictive maintenance [2], which uses technical condition monitoring technologies [3, 4]. There are several condition monitoring techniques available, including vibration analysis, thermography, strain measurement and self-diagnostic sensors. The wind turbine blades are typically at a maximum size of 55m in length, with expected increases soon up to 80m for offshore wind turbines [5]. With such large scales involved they are difficult to measure, and therefore a novel approach to laser mounting and axes of measurement is required so that a laser scanner can track the turbine blades and determine a real measure of alignment [6, 7].

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.10.041

2. Wind Turbine Blade Alignment

Turbine blade alignment [8, 9] focuses on ensuring that each blade is acting with its angle at the optimum (often perpendicular) angle to the blade hub, that is ensuring the greatest blade length is presented to the oncoming wind, and that the aerodynamic optimisation of the blade (and the control of loading with blade pitch) is acting at its correct optimum operating set-point [10]. In order to achieve this, the blades of an axial wind turbine need to be aligned, that is, at a variety of span-wise locations, the deviation in axial location of the blade is nominal between the blades (for which one blade can be checked to be correctly aligned to the hub). There are numerous degrees of freedom of blade alignment, as detailed by WindComp [10] in Figure 1, with many of these being assessed at installation, for example, blade twist, blade pitch and blade radial alignment. However, blade axial alignment requires separate measurement in the field. During such a test, the blades will be constantly rotating, and deflecting under varying loads as they rotate.

Fig. 1. Degree of freedom of blade alignment

3. Ensemble Averaging

Ensemble averaging simply aims to gain the accuracy improvements that come through repeating experiments and averaging, but doing so for periodic results. The method of ensemble averaging is used throughout this paper to reduce multiple periods of data into a single period, by which the method takes numerous sets of data and outputs a far more accurate and cleaner single period trace. The process is diagrammatically described in Figure 2, with the process being to use a trigger signal (that is a TTL voltage which rises from 0-5v as a certain point on the shaft passes a sensor) to determine a rotational datum, and then based upon the time taken between triggers, the average rotational speed can be determined for each period. It is then trivial to simply average the same period-wise location for multiple periods into a single period, with the time base being based on the average period time of the raw measurement results. The advantage of this technique is that it removes noise from the data and provides a more accurate result that has spurious or atypical results suppressed. This means that shafts or turbine fans can operate at their standard rotational rates during measurement taking, which would often be greater than the ideal rate for optimal resolution of the measurement device. Therefore, data can be collected in real-time, and compensates for the constraint of laser response rate by taking numerous sets of measurements.

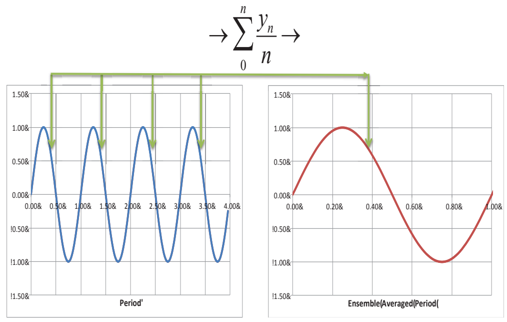

Fig. 2. Blade mid-span deflection measurements made by laser measurement

4. Real-time Alignment Measuring – Laboratory Study

Wind turbine blades operate in a dynamic environment, where they operate at different pitch angles, with differing wind speed and often with an oncoming wind varying in axial velocity and angle over the height of the turbine. As such, each blade will experience a range of loadings, varying both throughout the blade's rotation and also span-wise along the radially axis of the turbine. Therefore, a turbine blade alignment process requires the blades to be able to move, yet still assess their alignment in terms of incidence to the hub (as opposed to pitch) even though each blade will, at an instantaneous moment in time, be under differing loading conditions [5], [6].

Table 1. Calculation of required laser response time

Rotation speed	120.00 rpm
Diameter	0.59 m
Circumference	1.84m
Blade width	0.05m
Time to rotate through one blade width	13.60 ms

Finally, in order to reverse engineer the results to determine blade deflection and movement to be scaled to a whole blade model, the data will then be inputted into a CAD model of the exact blade to show how using such span-wise results can be further evaluated to visualise a whole blade's deflection in a computer model. Differing span locations will be recorded by varying the laser's angle of incidence, and using the laser's built-in hardware, which uses both flight-of-time and a laser wave phase to determine accurate distance measurements. The assembly of the rig is shown in Figure 3.

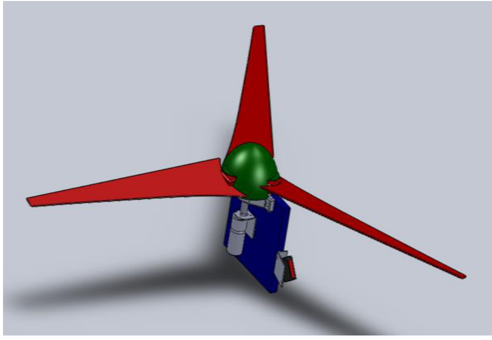

Fig. 3. Blade alignment test rig

5. Experimental Results

5.1. Test Plan

A test rig was assembled using 3 turbine blades, connected via a hub and fan shaft to a motor, using 3.0 volts as the DC motor voltage setting, offering around 120rpm nominal test speed. A distance measurement laser was mounted as would be located on the nacelle of the turbine, but equally could be mounted on the support pylon of a wind turbine.

The laser was calibrated using the data logger reading 4,096 readings at 1,024Hz for two measurement locations (the first at 400mm, the second at 8,000mm to get a voltage change over a large distance to gain an accurate V/mm gradient). The results were highly sampled, with 2 x 4s of data going into each point of the calibration gradient. The dependent variable, that is, the analogue voltage output from the laser, and the independent variable, that is, distance, recorded from an LED screen off the laser device, were recorded and the resultant change in voltage by distance change gradient was calculated. A voltage to distance multiplier of $2{,}839^{-1}$ V/mm was derived from the calibration test, and therefore the voltage reading for the data logger during the experiment was multiplied by this value to convert the voltage from the laser back into a distance.

The test plan was as follows:

1. Measurement of blade tip (radial distance 550mm) region, no deflection weight
2. Measurement of blade tip (radial distance 550mm) region, with 200g deflection weight
3. Measurement of blade mid-span (radial distance 350mm) region, no deflection weight
4. Measurement of blade mid-span (radial distance 350mm) region, with 200g deflection weight

5.2. Outer Measurement location, no Deflection

Figure 4 and Figure 5 display the results of the time history and ensemble averaged data measuring the tip location of the turbine blade. The results show a clear trigger signal being recorded, which has generated a clean ensemble averaged trace. The laser measurement has had its datum set to one of the blades, and therefore the result of the minima asymptote of each trace shows the change, in millimetres, of the blade's position. It can be seen that in this case the blades are all within $^{+}$/-0.2mm of one another, suggesting good alignment, recorded at a rotational speed of 120rpm.

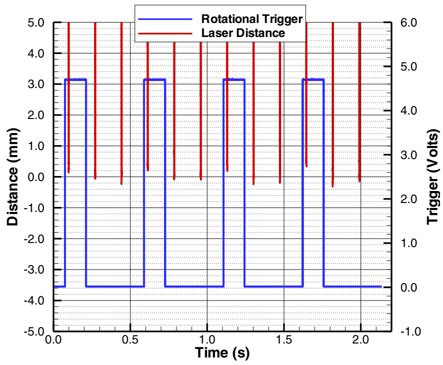

Fig. 4. Outer location, no weight, time history data

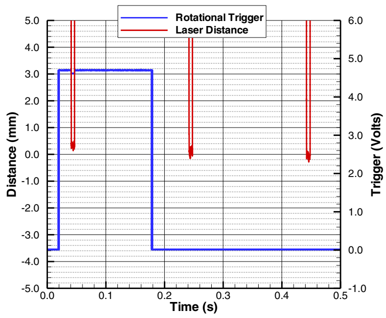

Fig. 5. Outer location, no weight, ensemble averaged data

5.3. Outer Measurement Location, with Deflection

When a 200g steel mass was placed at a far span (r=450mm) onto one blade, blade deflection occurs, simulating misalignment. Reviewing the results given in Figure 6 and Figure 7 for the time history and ensemble averaged data, it is clear which blade is out of alignment from the datum (no deflection) condition of being the first blade passing after the trigger signal, with a deflection of -2.1mm relative to the other blades. This deflection is clear and was determined in real-time.

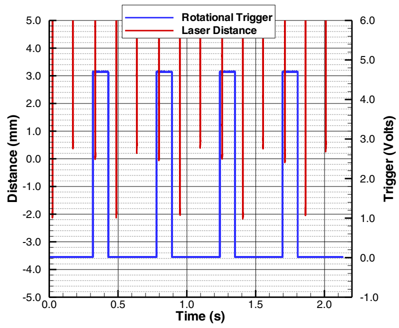

Fig. 6. Outer location, weighted, time history data

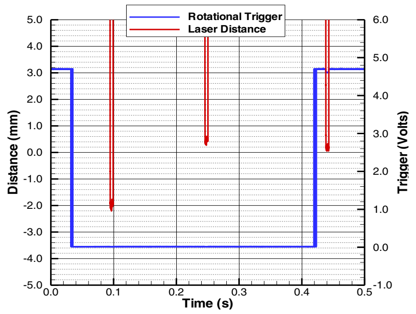

Fig. 7. Outer location, weighted, ensemble averaged data

5.4. Inner Measurement Location, no Deflection

Moving to a more inner radial measurement location, at r=350mm, with the 200g deflection weight removed, the results can be seen in Figure 8 and Figure 9. The width of the measurement minima asymptote is longer in time as the blade width is greater at this location, and again the blades can be seen to be in close alignment, less than +/-0.2mm between them.

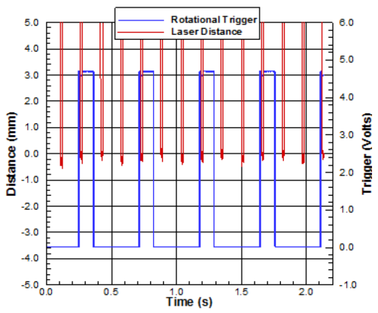

Fig. 8. Inner location, no weight, time history data

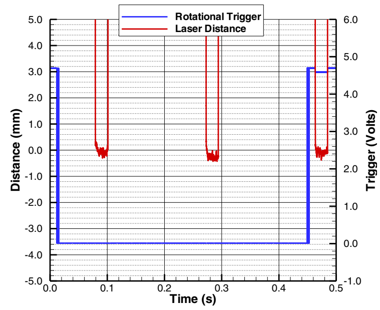

Fig. 9. Inner location, no weight, ensemble averaged data

5.5. Inner Measurement Location, with Deflection

Figure 10 and Figure 11 show the results at the mid-span (r=350mm) measurement location, but now with the 200g steel mass placed at r=450mm, causing blade deflection. It can be seen clearly that the middle blade, from the trigger's rising edge signal, is out of alignment by -0.9mm, a result that is especially clear in the time history trace. Again, the laser has shown the ability at relatively high rotational speed to accurately detect blade misalignment. The trace at the minima asymptote also shows the rough profile of the blade, as the angle of the blade can clearly be seen.

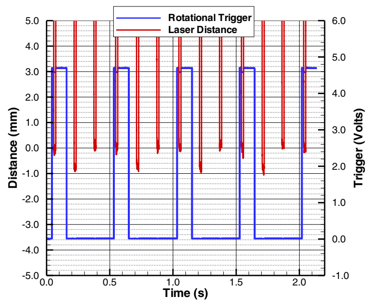

Fig. 10. Inner location, weighted, time history data

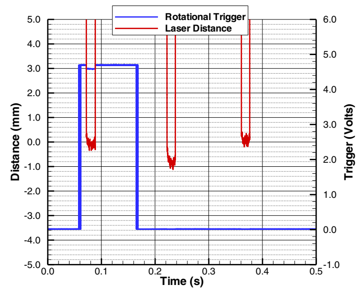

Fig. 11. Inner location, weighted, ensemble averaged data

6. Conclusions

This paper has shown test rigs and processing techniques that are able to, in real-time, determine the degree of alignment in turbine blade set up. By using sets of lasers on a wind turbine blade alignment rig, and then determining the average and periodic amplitude from an ensemble averaged signal, the degree of misalignment can be found and the necessary corrective action taken. The turbine blade test rig showed the ability to rapidly, and in real-time, assess blade alignment from a nacelle or tower-mounted laser measurement device and determine easily which blade needed re-alignment.

Acknowledgements

The authors would like to acknowledge the funding received from the UK EPSRC Centre for Through Life Engineering Services (EP/1033246/1, Project SC006). UK EPSRC Impact Acceleration Account Award (EP/K 50336811), UK Royal Academy of Engineering Newton Research Collaboration Programme (NRCP/1415/91) and UK Royal Society- National Natural Science Foundation of China International Exchanges Award (IE150600).

References

[1] Digest of the United Kingdom energy statistics (DUKES), Renewable Sources of Energy, Chapter 6. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/450298/DUKES_2015_Chapter_6.pdf

[2] Pruftechnik, Wind Industry Technology, PRüFTECHNIK Alignment Systems GmbH, Ismaning, 2012.

[3] Farrar CR, Worden K. An introduction to structural health monitoring", Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), 2007, 303-315.

[4] Lu B, Li YY, Wu X, Yang, ZZ, A review of recent advances in wind turbine condition monitoring and fault diagnosis, in IEEE power electronics and machines in wind applications conference, 2009.

[5] Wind Turbine Blade Structural Engineering. Wind Energy Handbook, Gurit

[6] Ozbek M, Rixen DJ, Verbruggen, TW, Remote monitoring of wind turbine dynamics by laser interferometry: Phase1, Department of Mechanical, Materials and Maritime Engineering Delft University of Technology Mekelweg 2, The Netherlands, 2009.

[7] Kim HC, Giri P, Lee JR, Real-Time Deflection Monitoring System for Wind Turbine Blades Using a Built-In Laser Displacement Sensor, 6th European Workshop on Structural Health Monitoring, Dresden, Germany, 3-6 July 2012.

[8] Rumsey MA and Paquette JA Structural Health Monitoring of Wind Turbine Blades, Sandia National Laboratories, Albuquerque, NM 87185.

[9] Yuji T, Bouno T, Hamada T, Suggestion of temporarily for forecast diagnosis on blade of small wind turbine", IEEJ Trans Power and Energy, vol 126, no. 7, 2006, pp. 710-711.

[10] Windcomp, Laser Based Geometry Measurement of Rotor-Blades, Hamburg: Windcomp, 2012.

[11] CDT, Terrestrial laser scanning specifications, Caltrans Surveys Manual, California Department of Transportation, 2011